CLOSED-ORBIT DISTORTIONS FOR "TYPICAL" AND "PACMAN" BUNCHES INDUCED BY THE PARASITIC COLLISIONS

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ABSTRACT

The dipole force on the beams caused by the parasitic collisions (PCs) induces closed orbit distortions in the interaction region. "Typical" bunches (those far away from the ion-clearing gap), collide center-on-center with a small horizontal crossing angle. "Pacman" bunches (those close to the gap) not only collide at an angle, but their centers are displaced as well. The orbit separation between the beams at the PCs is different from nominal. In this note we evaluate these effects as a function of horizontal tune in first-order approximation. In general, we conclude that the crossing angle and orbit displacements are very small except for tune values very close to the integer (above or below), and that fractional tunes $\gtrsim 0.35$ are clearly, though weakly, favored.

1. Introduction.

The PEP-II design[1] calls for head-on collisions with magnetic separation in the horizontal plane. This separation scheme entails unavoidable parasitic collisions (PCs) near the interaction point (IP) whose effects on the beam-beam dynamics have been studied quite extensively.[1,2] It has been found that the PCs can introduce significant horizontal-vertical coupling that has the tendency to blow up the beams preferentially in the vertical plane, especially the low-energy beam (LEB). These studies have established a constraint on the minimum beam separation at the first PC, which PEP-II satisfies amply.

In this note we address another effect of the PCs: the net attractive force between the beams distorts the closed orbits of the two beams. We are only concerned with two aspects of this closed-orbit distortion: an induced horizontal crossing angle, and a change in the orbit separation at the PCs. If the beams were uniformly populated, the crossing angle would be the same for all bunches. However, the existence of an ion-clearing gap complicates matters a bit: those bunches near the head or the tail of the train (dubbed "pacman bunches") experience crossing angles different from those bunches in the middle of the train, and collide off-center due to the imbalance of the net forces to the right and to the left of the IP. Bunches away from the head or tail of the train (dubbed "typical") experience only a crossing angle without orbit separation.

Obviously the magnitude of these effects depends on the horizontal tune. We conclude that the effects are generally quite small unless the tune is very close to an integer value (from below or from above). Tune values $\gtrsim 0.35$ are clearly, though weakly, preferred. The first and last Pacman bunches experience the largest orbit separation at the IP. Typical bunches experience the largest shift in orbit separation at the PCs and the largest crossing angle at the IP. We do not assess here the effects of these shifts on beam dynamics; however, existing results[3,4] tend to show that orbit distortions of the magnitude found here are not likely to have a significant detrimental effect on the luminosity performance of the machine.

The results of this note correct, complete and update earlier preliminary results.[5]

2. Assumptions.

We assume that the basic beam and lattice parameters of the IR are given by Tables 1–3 (although the parameters of Table 3 are not used in this note, we include them here for future reference). The optics and geometry of the IR are assumed symmetric about the IP. In addition, we assume that the ion-clearing gaps in both beams are of the same length, and that the beams are stored in such a way that gaps "collide" with gaps and beams with beams. In other words, we assume that the bunch at the head of the train in one beam collides at the IP with the bunch at the head of the train in the other beam.

Table 1. PEP-II primary parameters.

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2199.32	2199.32
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
N	5.630×10^{10}	2.586×10^{10}
I [A]	2.147	0.986
ε_{0x} [nm-rad]	61.27	45.95
ε_{0y} [nm-rad]	2.451	1.838
β^*_x [m]	0.375	0.500
β^*_y [m]	0.015	0.020
σ^*_{0x} [μm]	151.6	151.6
σ^*_{0y} [μm]	6.063	6.063
σ_ℓ [cm]	1.0	1.0

Table 2. PEP-II IR parameters.

LEB							
k	d [mm]	β_x [m]	β_y [m]	α_x	α_y	ν_x	ν_y
0	0.0	0.375	0.015	0.0	0.0	0.000	0.000
1	3.498	1.433	26.460	–1.679	–41.98	0.165	0.246
2	17.651	4.607	105.63	–3.362	–83.77	0.204	0.248
3	39.114	16.202	133.70	–11.79	–27.96	0.215	0.249
4	71.879	57.171	69.294	–40.76	+34.98	0.218	0.250
HEB							
0	0.0	0.500	0.020	0.0	0.0	0.000	0.000
1	3.498	1.293	19.853	–1.260	–31.49	0.143	0.245
2	17.651	3.673	79.340	–2.519	–62.96	0.190	0.247
3	39.114	9.162	148.29	–5.322	–64.50	0.207	0.248
4	71.879	20.917	189.97	–10.94	–39.35	0.214	0.249

Table 3. Other PEP-II IR parameters.

LEB							
k	s [m]	η_x [m]	σ_{0x} [mm]	σ_{0y} [mm]	d/σ_{0x}	ξ_{0x}	ξ_{0y}
0	0.0	0.000	0.151573	0.006063	0.0	0.03	0.03
1	0.630	0.002	0.296	0.255	11.8	–0.000224	0.004133
2	1.260	0.024	0.531	0.509	33.2	–0.000028	0.000648
3	1.889	0.061	0.996	0.572	39.3	–0.000020	0.000167
4	2.519	0.138	1.872	0.412	38.4	–0.000021	0.000026
HEB							
0	0.0	0.000	0.151573	0.006063	0.0	0.03	0.03
1	0.630	0.001	0.244	0.191	14.3	–0.000152	0.002326
2	1.260	0.009	0.411	0.382	43.0	–0.000017	0.000365
3	1.889	0.017	0.649	0.522	60.3	–0.000009	0.000139
4	2.519	0.028	0.980	0.591	73.3	–0.000006	0.000053

3. Calculation.

Relative to the nominal orbit, the closed orbit distortion X_o and slope X'_o at an observation point o produced by discrete kicks $\Delta X'_k$ are given, in first order in $\Delta X'_k$, by the expressions

$$X_o = \frac{\sqrt{\beta_o}}{2\sin\pi\nu}\sum_k \Delta X'_k \sqrt{\beta_k}\cos(\Delta\phi_k - \pi\nu) \tag{3.1}$$

and

$$X'_o \equiv \frac{dX_o}{ds} = \frac{1}{2\sqrt{\beta_o}\sin\pi\nu}\sum_k \Delta X'_k \sqrt{\beta_k}\left(\sin(\Delta\phi_k - \pi\nu) - \alpha'_o\cos(\Delta\phi_k - \pi\nu)\right) \tag{3.2}$$

where the $\Delta\phi_k$ is the horizontal phase advance of point k relative to the o and ν is the horizontal tune. $\Delta\phi_k$ must be ≥ 0 for all k; i.e., these phase advances must be computed by going from o to k in the same sense around the ring for all k. The slope X'_o is discontinuous whenever o coincides with any point k for which $\Delta X'_k \neq 0$. In our case, the kicks $\Delta X'_k$ are produced by the PCs. Each bunch experiences four PCs on either side of the IP, as sketched in Fig. 1, and these PCs are labeled $k = -4,...,4$.

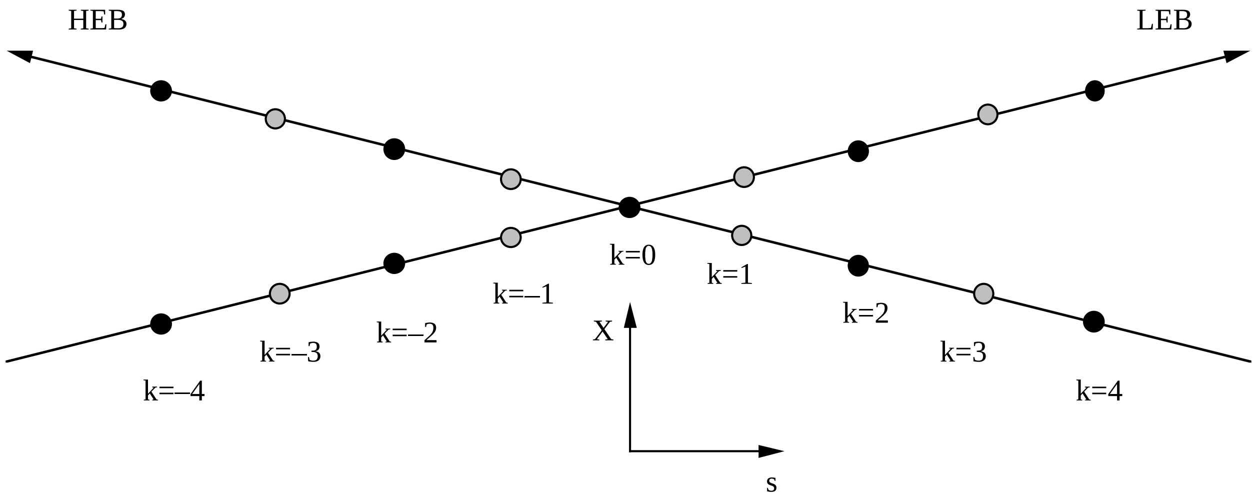

Fig. 1: Plan sketch of the IR showing all four PCs on either side of the IP. Solid black bunches are shown in their actual position. Gray bunches show the positions of the PCs when the bunches move by $s_B/2$.

If the horizontal displacement x and azimuthal coordinate s (for both beams) point in the direction as sketched in Fig. 1, then the kicks for $k \geq 1$ are given by

$$\left.\begin{aligned} \text{LEB:}\quad \Delta X'_k &= -\frac{2r_0 N_-}{\gamma_+ d_k} \\ \text{HEB:}\quad \Delta X'_k &= +\frac{2r_0 N_+}{\gamma_- d_k} \end{aligned}\right\} \quad \text{for } k = 1,\cdots,4 \tag{3.3}$$

while those for $k \leq -1$ are given by

$$\Delta X'_{-k} = -\Delta X'_k \tag{3.4}$$

for each beam. The kick at the IP, $\Delta X'_0$, is zero in first approximation for all bunches. In the above expressions r_0 = 2.815 × 10^{-15} m is the classical electron radius, the γ's are the usual relativistic factors, and the N's are the numbers of particles per bunch. If the observation point is the IP, the relative phase advances are

$$\Delta\phi_k = \begin{cases} 2\pi\Delta\nu_k, & k = 1,\cdots,4 \\ 2\pi(\nu - \Delta\nu_{-k}), & k = -4,\cdots,-1 \end{cases} \tag{3.5}$$

where the $\Delta\nu$'s are the horizontal phase advances listed in Table 2. For other observation points (e.g., at a PC location), some of these phase advances may have to be shifted by $2\pi\nu$. Whatever the observation point is, the phase advance $\Delta\phi_o$ is given by

$$\Delta\phi_o = \begin{cases} 0, & s = o_- \\ 2\pi\nu, & s = o_+ \end{cases} \tag{3.6}$$

4. Results.

The design calls for a train of 1658 bunches followed by an ion-clearing gap of length equivalent to 88 bunches. Since each bunch could, in principle, experience a collision at the IP plus four PCs on either side of the IP, there are four Pacman bunches at the head of the train and four at the tail. The bunch at the head of the train is labeled Pacman bunch #1, the one at the very end #–1. The other bunches are labeled as shown in Fig. 2.

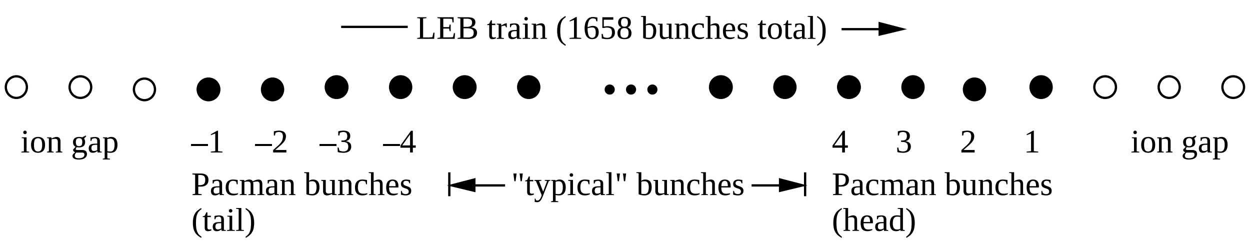

Fig. 2: Sketch of the bunch population of the LEB. There are four Pacman bunches at the head of the train, four at the tail, plus 1650 "typical" bunches. For our purposes, we label the bunches as shown. The HEB is similar, except that it moves in the opposite direction, with similar labeling: the very first bunch at the head of the train is labeled Pacman bunch #1, etc.

As mentioned above, we assume that the ion-clearing gaps in both beams are of the same length, and that the beams are filled such that the head bunch of the LEB collides at the IP with the head bunch of the HEB. Therefore pacman bunch #1 of the LEB experiences collisions k = 0, 1, 2, 3 and 4, where 0 is the main collision at the IP; bunch #2 experiences collisions k = –1, 0, 1, 2, 3 and 4; bunch #–1, k = –4, –3, –2, –1 and 0, etc. Similarly, pacman bunch #1 in the HEB experiences PCs k = –4, –3, –2, –1 and 0, and so on. The remaining 1650 bunches in the middle of the trains of both beams experience all nine collisions, namely k = –4, ... , 4. We call these "typical" bunches.

4.1 Results for typical bunches.

The orbit distortion, Eq. (3.1), is a periodic function of ν with period 1. Thus only thhe fractional part of the tune matters. It is also easily seen from Eqs. (3.1–5) and the symmetry of the IR optics that the orbit distortions at PCs to the left of the IP (k = –1, ... , –4) are of the same magnitude and opposite sign as those to the right of the IP. Similarly, the orbit distortion of a tail pacman bunch is of the same magnitude and opposite sign as that for the corresponding pacman bunch at the head of the train. Therefore we shall only provide results for $0 < \nu < 1$, for typical or head pacman bunches at the IP or PCs to the right of the IP. These results constitute a complete set on account of the symmetries.

The symmetry of the IR optics imply that typical bunches have no closed orbit displacement at the IP, namely $X = 0$. On the other hand the slope X', given by Eq. (3.2), is nonzero, leading to a finite crossing angle. Fig. 3 shows the slopes at a point immediately upstream of the IP for LEB (refer to Fig. 1) for both beams and the full crossing angle, $\phi \equiv X'_{+}-X'_{-}$ (the crossing angle curve assumes the same fractional tune for both beams). It should be noted that the crossing angle is quite small: for $\nu = 0.64$, a value that has been used in many simulation studies,[1,2] the crossing angle is $\phi = 34.2$ μrad, which is much smaller than $\sigma_x/\sigma_\ell = 15.6 \times 10^{-3}$. Even for a fractional tune as high as 0.9, the crossing angle is 0.13 mrad. Therefore the effect on the beam-beam dynamics from this crossing angle is expected to be negligible.

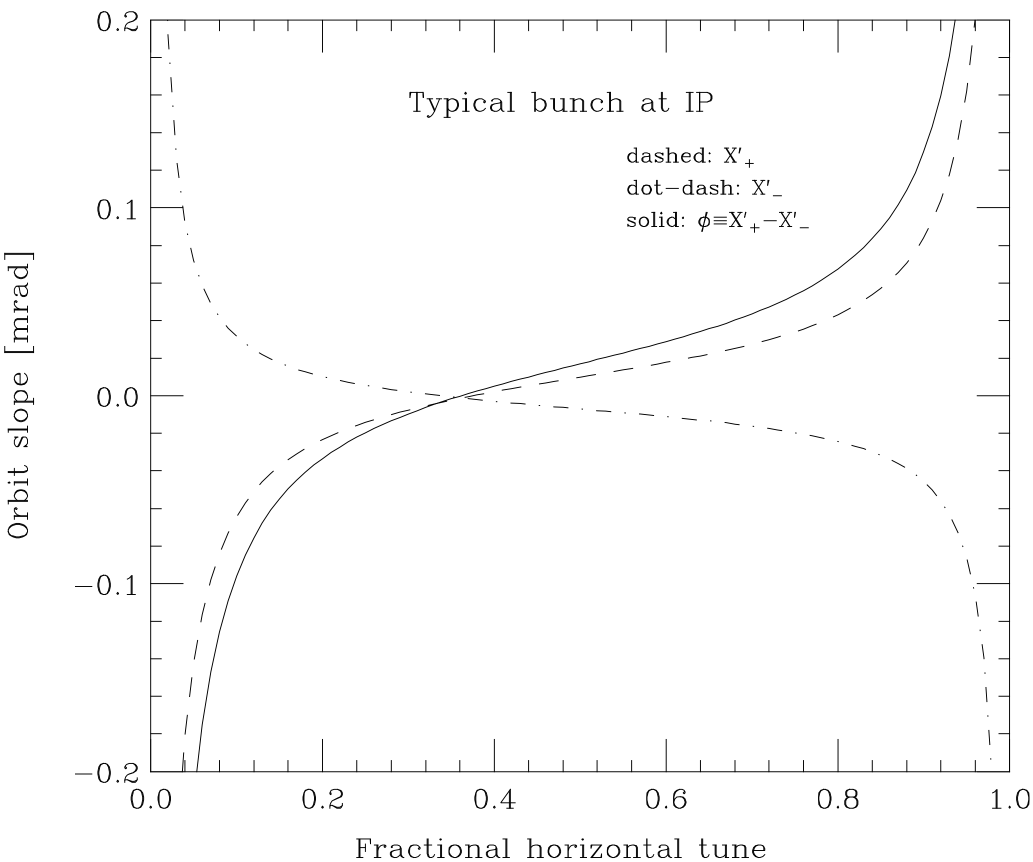

Fig. 3: Horizontal slopes at a point immediately upstream of the IP for the LEB, and full crossing angle of typical bunches. The crossing angle is computed assuming the same fractional tunes in both beams.

As mentioned earlier, the nominal beam separation at the first PC, d_1, has been the object of extensive simulation studies[1,2] and experiments.[6] The PEP-II nominal value, d_1 = 3.5 mm (see Table 2), corresponds to $d_1/\sigma_{0x,+}$= 11.8, which is generally believed to be large enough that the effects from PCs on the beam dynamics are negligible. It is important, therefore, to calculate the change in d_1 induced by the PCs. Fig. 4 shows the orbit distortions of both beams for typical bunches at the 1st PC, and Fig. 5 shows the fractional change of the beam separation, $\Delta d/d$, produced by the orbit distortion at all PCs. Clearly the orbit distortion at the 1st PC is the most significant. An increased beam separation is favorable from the point of view of the beam-beam dynamics, so the results in Fig. 5 favor fractional tunes $\nu \gtrsim 0.4$. However, the effect is too small to be of any practical consequence whether the separation is increased or decreased: for the tune range $0.1 \lesssim \nu \lesssim 0.9$, $\Delta d/d$ is less than 2% in absolute value at all PCs. For $\nu = 0.64$, the relative orbit separation shift at the 1st PC, $\Delta d_1/d_1$, is 0.6%, which is totally negligible.

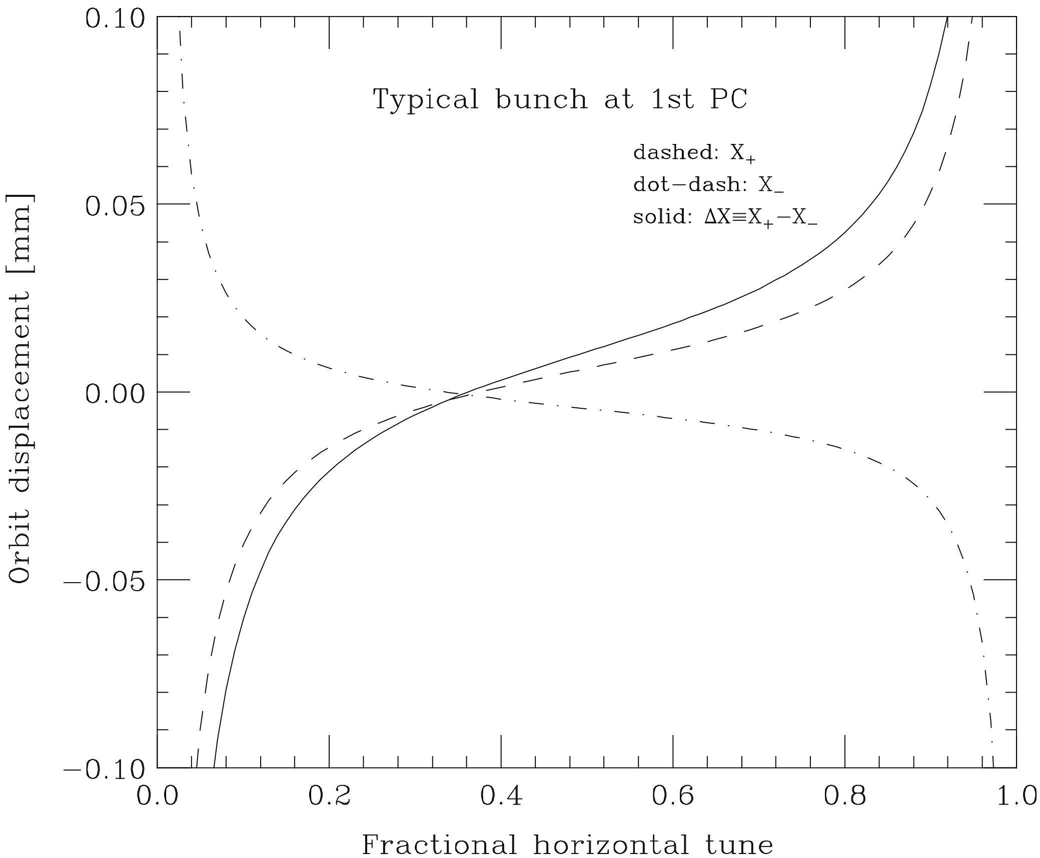

Fig. 4: Orbit distortions of typical bunches at the 1st PC. The change in orbit separation ΔX is computed assuming that the two beams have the same fractional tune.

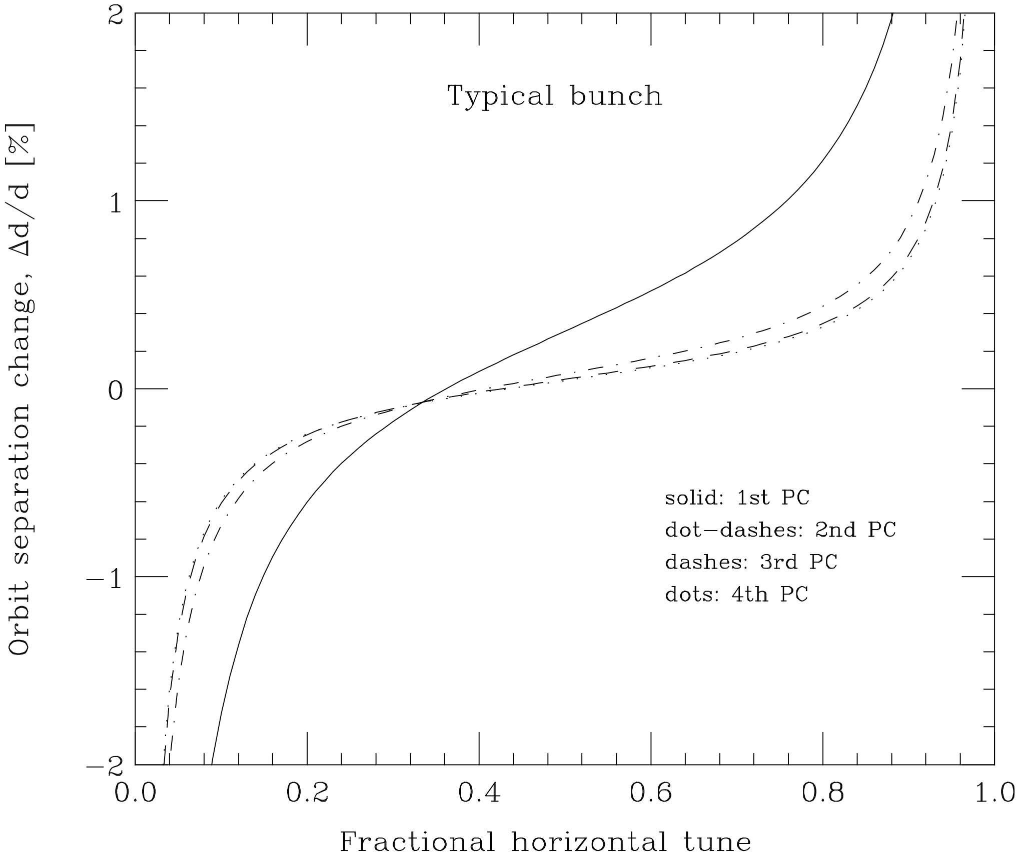

Fig. 5: Fractional change of the orbit separation of a typical bunch at all PCs ($\Delta d \equiv \Delta X$). The two beams are assumed to have the same fractional tune.

4.2 Results for Pacman bunches at the IP.

Fig. 6 shows the orbit slopes of the 1st pacman bunches at the IP. Comparing with Fig. 3, one can see that the slopes for the 1st pacman bunch are ~1/2 of those for a typical bunch. This makes physical sense: the 1st pacman bunch receives ~1/2 of the integrated kick that a typical bunch receives.

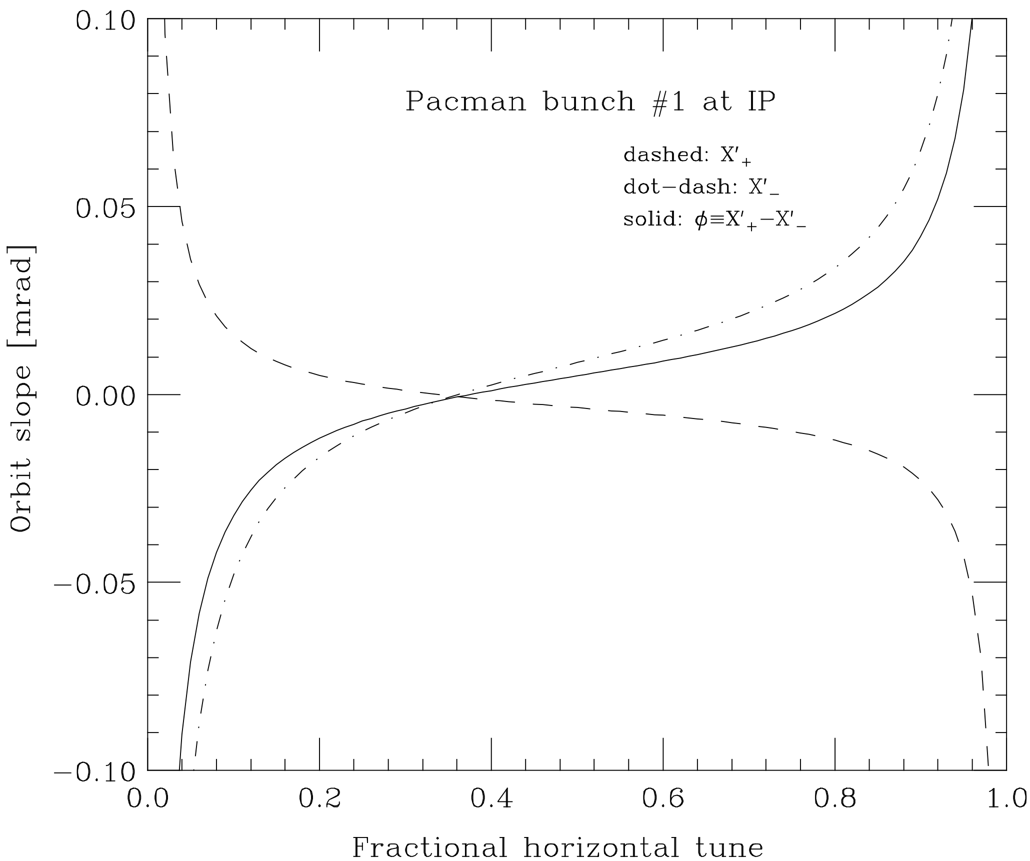

Fig. 6: Horizontal slopes at a point immediately upstream of the IP for the LEB, and full crossing angle, of the 1st pacman bunches. The crossing angle is computed assuming the same fractional tunes in both beams.

Fig. 7 shows the absolute and relative displacements of the orbits of the 1st pacman bunches at the IP. It should be noted that, for most values of the fractional tune, both bunches are displaced to the *same side* of the nominal orbit (X_+ and X_- are of the same sign). This makes physical sense: referring to Fig. 1, there is a net imbalance of the forces from the PCs such that the head bunches of *both* beams are pulled in the $x < 0$ direction. By symmetry, the last bunches at the tails of the beams are pushed towards $x > 0$ by the same amount as the head bunches are pushed towards $x < 0$. The magnitude of the displacement of the 1st pacman bunch from its nominal orbit is $\lesssim 10$ μm for most values of the tune. More interestingly, the displacement of one bunch *relative to the other*, which is what matters for the beam-beam dynamics, is $\Delta X < 2$ μm. These numbers are small compared to the rms bunch width of 152 μm.

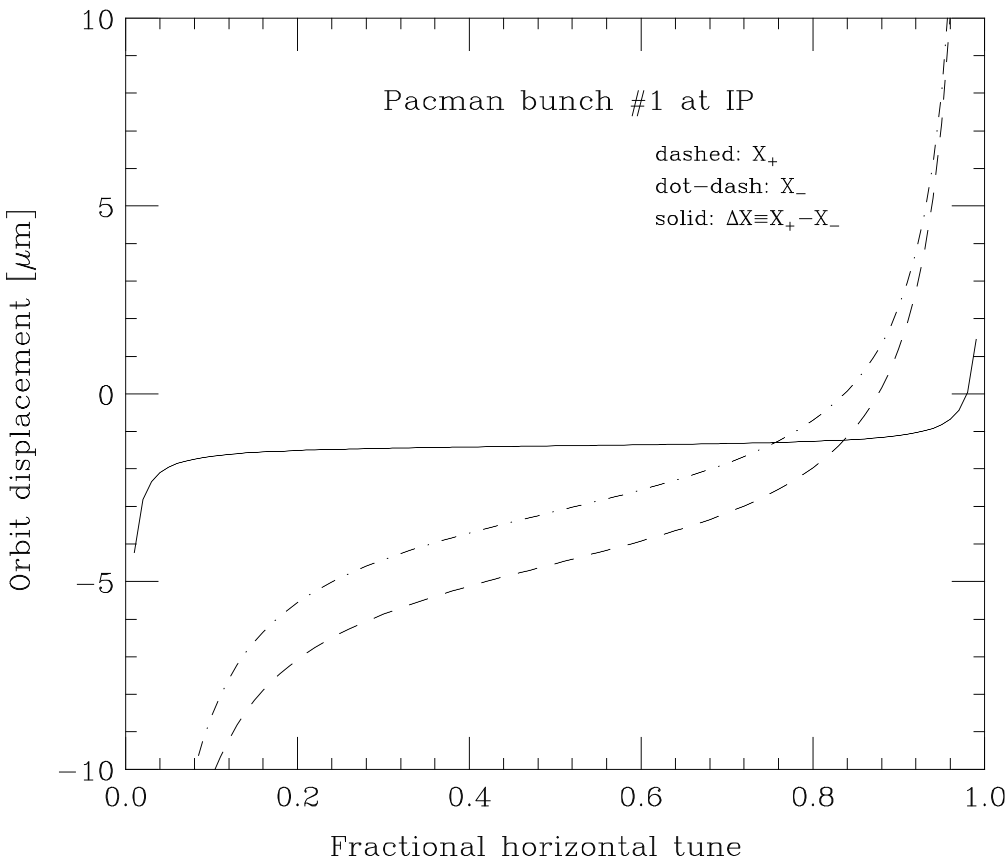

Fig. 7: Orbit distortions of the head pacman bunches at the IP. The change in orbit separation ΔX is computed assuming that the two beams have the same fractional tune.

Fig. 8 shows the absolute orbit separation between the two beams at the IP for all four pacman bunches at the head of the train. It is clear that the largest effect is for the 1st pacman bunch (we recall that typical bunches have zero separation at the IP).

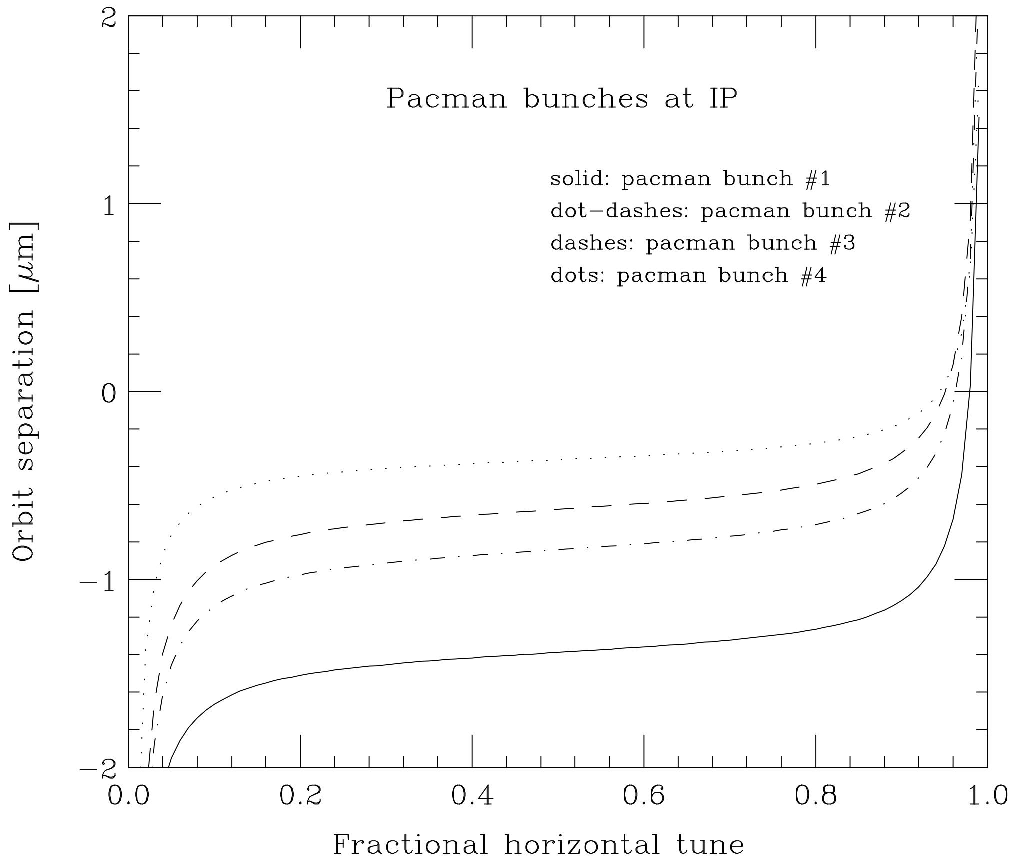

Fig. 8: Beam orbit separation at the IP for all four head pacman bunches.

4.3 Results for Pacman bunches at the PCs.

Fig. 9 shows the orbit displacements of the 1st pacman bunch of the LEB and the 2nd pacman bunch of the HEB at the 1st PC, which is where they collide. The shift in separation is less than 0.1 mm in absolute value for most tune values, which is small compared to the nominal orbit separation, d_1 = 3.5 mm. Comparing with Fig. 4, one sees that the results are very similar to those for a typical bunch.

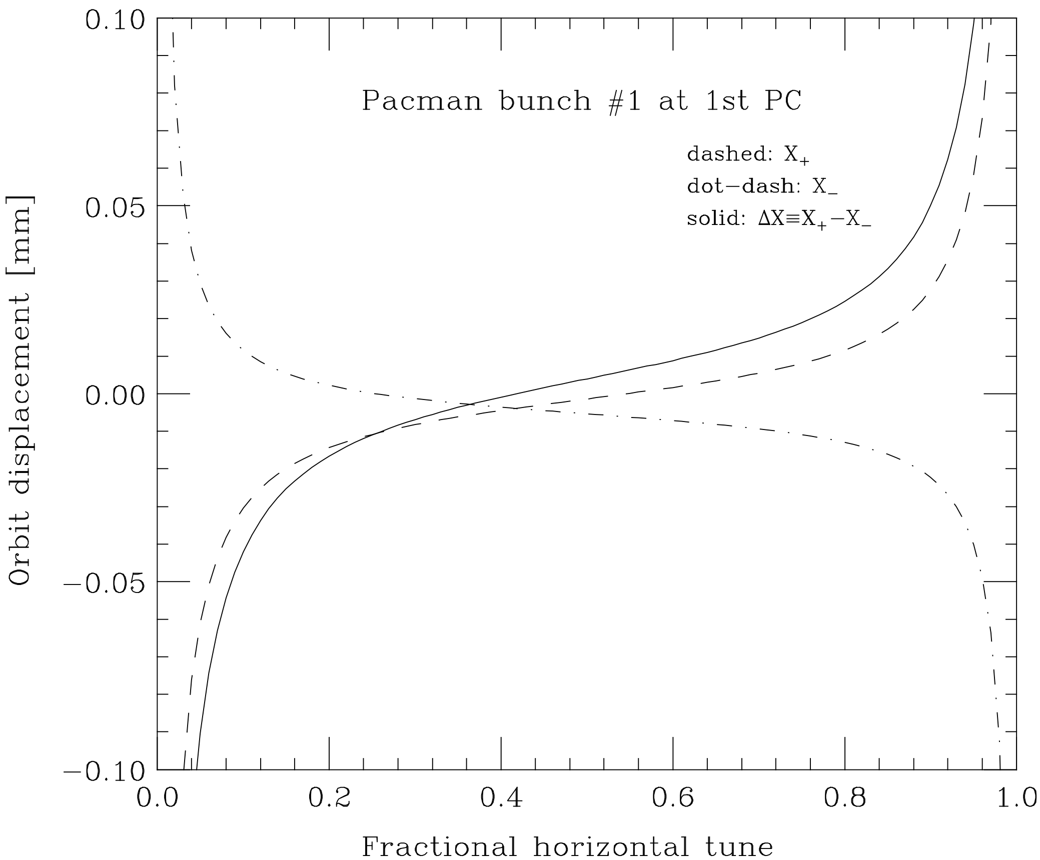

Fig. 9: Orbit distortions for LEB pacman bunch #1 and HEB pacman bunch #2 at the 1st PC. The change in orbit separation ΔX is computed assuming that the two beams have the same fractional tune.

Fig. 10 shows the relative change in orbit separation for the 1st LEB pacman bunch as it collides with HEB bunches #3, 4 and 5 at PCs #2, 3 and 4, respectively. These results should be compared with those for a typical bunch in Fig. 5. One sees that the orbit separation shift for the 1st pacman bunch is ~1/2 of that for a typical bunch, for the reason mentioned earlier.

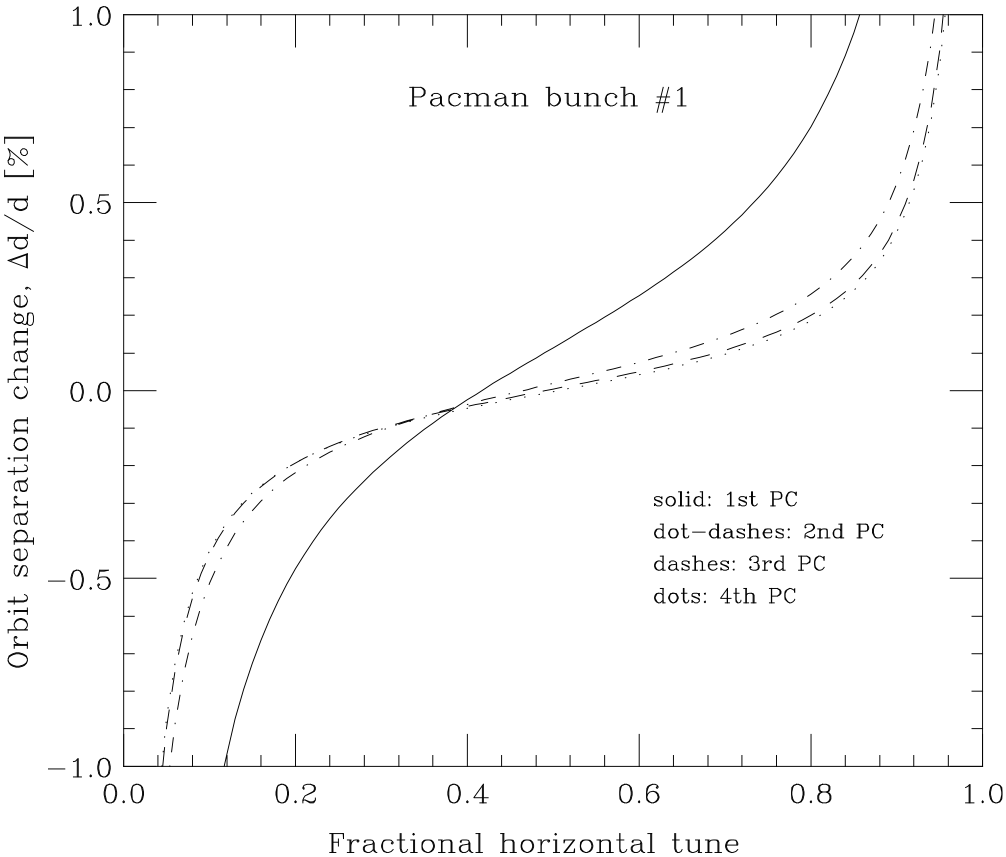

Fig. 10: Relative change in orbit separation at all PCs of LEB pacman bunch #1 as it collides with HEB bunches #2, 3, 4 and 5. The two beams are assumed to have the same fractional tune.

Finally, Fig. 11 summarizes the relative orbit separation shift for all bunches at the 1st PC. As should be expected, the result for pacman bunches #2, 3 and 4 interpolate smoothly between those for a typical bunch (shown earlier on Fig. 5) and the 1st pacman bunch (shown in Fig. 10).

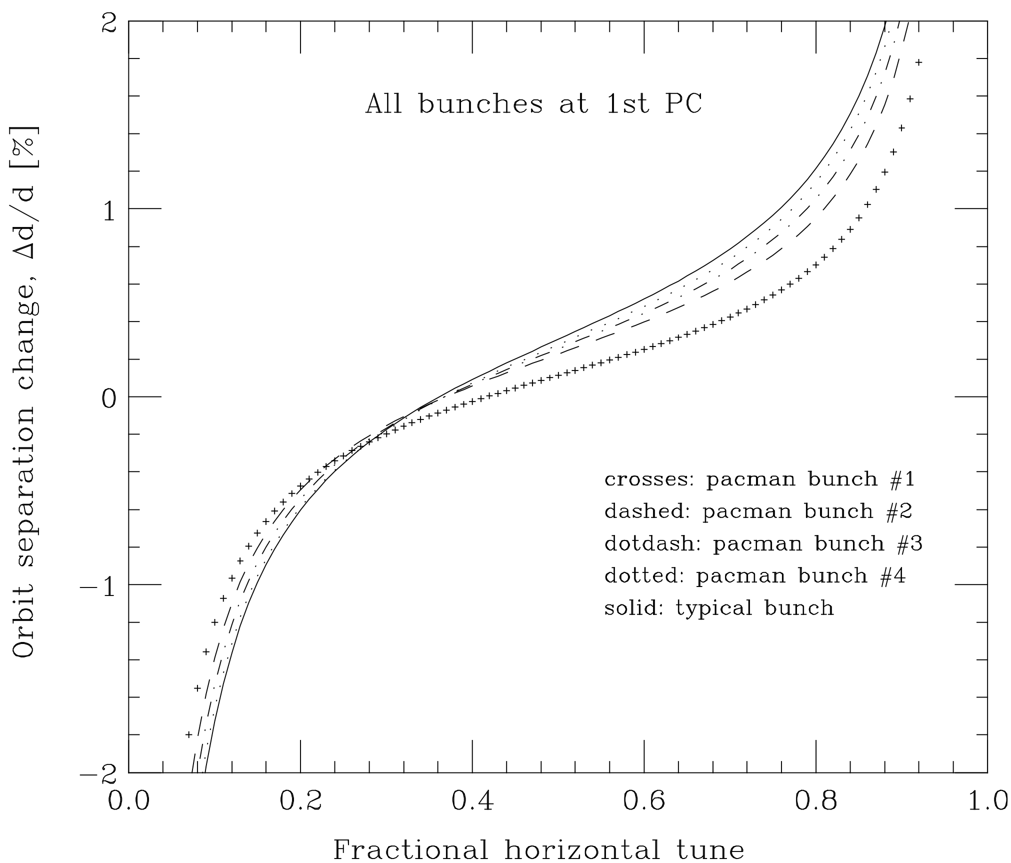

Fig. 11: Relative change in orbit separation at the 1st PC for all bunches. The curve for the typical bunch is copied from Fig. 5, and that for the 1st pacman bunch from Fig. 10.

5. Discussion and conclusions.

In general, we conclude that closed orbit effects from the PCs are so small for nominal PEP-II beam parameters that they are expected to have negligible effects on the dynamics. More specifically, our results can be summarized as follows:

5.1 Crossing angle.

For sensible horizontal tunes (fractional part in the range $0.15 \lesssim \nu \lesssim 0.85$), typical bunches collide with a horizontal crossing angle $|\phi| \lesssim 0.1$ mrad, assuming the same fractional tune for the two beams. The 1st pacman bunch collides at a smaller angle, $|\phi| \lesssim 0.05$ mrad, and the other pacman bunches collide at angles in between 0.05 mrad and 0.1 mrad. It is always possible to cancel the crossing angle provided that one beam has fractional tune > 0.35 and the other < 0.35. In any case, the crossing angle is much smaller than the ratio $\sigma_x / \sigma_\ell = 15.6 \times 10^{-3}$, and therefore this effect is expected to be negligible.

5.2 Orbit separation.

Pacman bunches collide off-center at the IP. The 1st pacman bunches at the head of the trains (and the last pacman bunches at the tail), have the largest orbit displacements. For fractional tunes in the range $0.15 \lesssim \nu \lesssim 0.85$, the bunch centers are displaced from the nominal orbit by $|X_\pm| \lesssim$ 10µm, which is $\lesssim$ 7% of the rms beam size, σ_x = 152 µm. Multiparticle simulations for displaced beams suggest that a separation of this magnitude should have a negligible effect on the luminosity performance. Even better, if the two beams have the same, or comparable, fractional tunes, the bunches in the two beams are displaced *to the same side* of the IP, so that their centers are displaced from each other by an even smaller amount, $|\Delta X| < 2$ µm, which is negligible. If the beams have substantially different fractional tunes, however, the bunch separation can be significant.

The beam separations of all bunches (typical and pacman) at all PCs are modified from the nominal values. At any given PC the fractional change in orbit separation, $\Delta d/d$, is largest for a typical bunch and smallest for pacman bunch #1. For any given bunch, the effect is largest at the 1st PC and smallest at the 4th PC. The change $\Delta d/d$ can be positive or negative depending on the value of the tunes of the two beams. If the fractional tunes of the beams are comparable and in the range $0.15 \lesssim \nu \lesssim 0.85$, the magnitude of the effect, $|\Delta d/d|$, is at most 1.5%, which is negligible.

5.1 Tune values.

The fractional change in orbit separation can be positive or negative depending on the fractional tune. A positive value indicates larger-than-nominal separation, which is favorable from the perspective of beam-beam dynamics. For all bunches, and for all PCs, $\Delta d/d$ is > 0 for $\nu \gtrsim 0.4$ and thus this is the favored range of tunes (assuming equal fractional tunes for the two beams). The crossing angle vanishes for $\nu \approx 0.35$, but it is not large for any reasonable value of the tune. Thus the dynamics weakly, but clearly, favors the range of fractional tunes $\nu \gtrsim 0.35$.

6. References.

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